Monsoonal Forcing of Zooplankton Variability in the Arabian Sea: Acoustic Measurements

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LONG-TERM GOALS

Many of the highly productive ecosystems of the world ocean are strongly forced physically and exhibit maxima in biomass and growth of zooplankton during bursts of phytoplankton growth. The role of the physical environment in shaping the community of zooplankton is difficult to study and can best be addressed in interdisciplinary studies using new instrumentation for quantifying biological response variables. Improved resolution of temporal and spatial variability of biomass of zooplankton and the physical environment are necessary steps before we obtain full understanding of mesoscale ecosystem questions.

OBJECTIVES

Basic questions concerning how populations of zooplankton perceive and respond to their habitats can be studied using the contrasting monsoonal regimes of the Arabian Sea. The biological transition in the upwelling area within 600 kilometers of the Oman coast from low productivity in April/May to high productivity in July-September is rapid, owing largely to the preadapted condition of the dominant zooplankton which persist throughout the non-upwelling seasons as late stage subadults in diapause. The rapid and widespread (Somalia to Oman) response of the zooplankton make it imperative that we maximize the use of high-frequency acoustic methods for estimating pelagic biomass. Our research objectives are: 1) to quantify seasonal and spatial variability in the biomass and community structure of mesozooplankton in the coastal upwelling regions of the Arabian Sea (Oman and Somalia), 2) to describe how the physical forcing creates the observed distributions, and 3) to quantify the effect of the oxygen minimum zone of the Arabian Sea on vertical distribution and vertical migration. This work is supported by ONR Biological Oceanography.

APPROACH

The northwestern Indian Ocean has properties unique to the world's oceans which can be used to expand our general understanding of production and population structure in the sea. Primary among these is the regular oscillation in physical forcing from upwelling/advection during one monsoon season (Southwest) to convection during the other major season, the Northeast Monsoon. Both occur in conditions of fairly constant illumination. In this investigation we are studying the seasonal and spatial

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variability of zooplankton and its relationship to the circulation of the Arabian Sea region using the acoustic Doppler current profiler (ADCP) mounted on the R.V. *Thomas Thompson* (in collaboration with C. Flagg, C. Ashjian, and I. Prusova). The combination of ship-mounted sensors and net sampling allows us to address larger spatial and temporal scales than have previously been studied. The investigation began in September 1994 and ended in January 1996; therefore, we have repeated ADCP profiles of the upper layer collected approximately monthly over the course of 16 months, accompanied by tows of a double one-meter MOCNESS and an ordinary one-meter MOCNESS. The *Thompson* had a program of 17 cruises. Backscatter intensity data from the acoustic Doppler current profiler and parallel MOCNESS tows were done on 5 cruises of the *Thompson*. Backscatter intensity is converted to biomass by an algorithm relating range-corrected backscatter intensity (Flagg, Brookhaven National Laboratory; Ashjian, Woods Hole Oceanographic Institution) and biomass of zooplankton (Smith) collected by the net systems. Size structure and community composition of the zooplankton are analyzed microscopically (Prusova, Institute of Biology of the Southern Seas, Sevastopol).

WORK COMPLETED

The 457 MOCNESS samples collected on R.V. *Thompson* have all had their displacement volume (biomass) measured and compiled into a database and report (Lane and Smith, 1997). Community structure analyses, including stage-structure of copepod, ostracod and euphausiid populations and size-structure of those populations, are nearly complete. These data will be published in at least two data reports (Lane et al., 1998a, b), one for each of two major cruises during the Northeast and Southwest Monsoon seasons. Of the 700 surface underway samples collected, only a few have been analyzed for the abundance of nauplii and subadult stages of zooplankton. Those analyses continue. The suite of underway sample positions and the associated surface temperature, salinity and chlorophyll fluorescence data from the R.V. *Baldrige* have been compiled into a database. The backscatter intensity data collected on the R.V. *Thompson* have been compiled into a database at Brookhaven National Laboratory. Sections of biomass generated from the backscatter intensity data have been created for the main south section sampled by all R.V. *Thompson* cruises and will be included in an regional atlas edited by Smith and Mariano.

RESULTS

Many new ideas about how the circulation and biogeochemical response of the Arabian Sea are connected are emerging. Based on AVHRR images, the response of the Arabian Sea to sustained southwest winds of high intensity during the summer is clear and direct. The area of upwelling, identified by cool sea-surface temperatures, increases markedly from early to mid-June and remains in that configuration, with variability associated with changes in wind strength, until mid-September. Once the Southwest Monsoon winds relax, upwelling may collapse quickly. Primary productivity was high throughout the year, supported by upwelling during the Southwest Monsoon and by convection in the Northeast Monsoon. In terms of zooplankton, the upwelling events and the existence of suboxic conditions below approximately 100 meters are major elements determining distributional patterns. The absolute maximum in biomass of epipelagic zooplankton was observed during the Southwest Monsoon season inshore of the Findlater Jet in the area of upwelling. (The Findlater Jet is the atmospheric jet whose canonical axis runs from Somalia to India through the middle of the study area; it is the dominant forcing feature of all the physical, biological and chemical variability observed in the Arabian Sea.) The greatest contrast between high and low biomass in the study area was also observed in the Southwest

Monsoon season, as was the strongest onshore-offshore gradient in biomass. Lowest biomass throughout the study was observed at the most offshore station, positioned outside the direct influence of the monsoon forcing. Seasonal peaks in biomass varied depending upon the subarea of the study region: in the upwelling area and most offshore area, the peak was in the Southwest Monsoon season; offshore of the Findlater Jet and in the most intensely suboxic area, the peak was in the Intermonsoon season.

Virtually no diel vertical migration took place in any season at the station with strong subsurface suboxic conditions, suggesting that these conditions suppress migration. The greatest day/night contrasts in biomass were observed nearshore in all seasons, with night-time biomass exceeding daytime in the Northeast Monsoon season, but daytime exceeding night-time in the Southwest Monsoon season. The diel vertical migration patterns in general reversed between the monsoons at all stations on the main, southern, sampling line. Based on the distribution of biomass, we hypothesize that inshore of the Findlater Jet mesozooplankton grazing on phytoplankton is the dominant pathway of carbon transformation during both monsoon seasons, whereas offshore the mesozooplankton feed primarily on microplankton or are carnivorous, conditions which result in reduced carbon flux mediated by the mesozooplankton. In the area of strong subsurface suboxic conditions, the food web operates like the offshore area during the Northeast Monsoon, but in the Southwest Monsoon there is potential for cell sinking to be an important factor in carbon flux because mesozooplankton biomass remains relatively low. Predation by mesopelagic fish, primarily myctophids, on mesozooplankton may equal daily growth of mesozooplankton inshore of the Findlater Jet during all seasons. This suggests that the food web inshore of the Findlater Jet is well integrated, may have evolved during past periods of intensified upwelling, and has a distinctly annual cycle.

IMPACT

This is one of a series of field studies that have demonstrated that the acoustic Doppler current profiler is a valuable instrument for assessing zooplankton biomass over spatial and temporal scales that can be matched to the scales used to evaluate physical forcing. This allows us to build our understanding of the quantitative linkages between physical forcing and zooplankton abundance in the sea. In the Arabian Sea we integrated multiple acoustic sensors for measuring zooplankton biomass into one program in which data can be carefully evaluated an compared. Acoustic Doppler current profilers have been used to investigate important ecological questions such as magnitudes and repeatability of vertical migration and timing and the timing and magnitude of spring outbursts of grazers in temperate latitudes.

TRANSITIONS

Following our initial use of the acoustic Doppler current profiler to estimate biomass of zooplankton in the Middle Atlantic Bight (Flagg and Smith, 1989), the instrument has been used by us in several other projects and by others in various regions including Antarctica. We have gained substantial understanding of zooplankton variability on the mesoscale from all these various efforts, understanding that would never have been possible with net tows alone. At the present time, RD Instruments produces a broad-band ADCP called the Workhorse which does not seem at all useful for the study of backscatter intensity in principle. RD Instruments has agreed to find a way to calibrate these instruments; an effort that is just beginning using three Workhorses here at The Rosenstiel School.

RELATED PROJECTS

This investigation eventually will be interpreted in the physical contexts observed by WOCE, NOAA, NASA, and the Forced Upper Ocean Dynamics ARI, and in the biogeochemical contexts observed by international and national JGOFS, NASA, and NOAA programs. Two data workshops have been convened by me (August 1996; July 1997) in which principal investigators from the ONR ARI (Forced Upper Ocean Dynamics) and the U.S. JGOFS program met together for ten days during each meeting. Data and ideas of approximately 65 principal investigators were freely discussed and new understanding evolved. The integration of these two programs into one scientific effort is one of my proudest achievements. At the present time I am editing the second of several special issues of *Deep-Sea Research* devoted to the combined programs. The first special issue, entitled, "The 1994-1996 Arabian Sea Expedition: Oceanic Response to Monsoonal Forcing, Part 1", will be published in December 1998. The number of submitted manuscripts is now 51, with an expectation of 20 or 25 manuscripts yet to be submitted.

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